ACCELERATOR LAYOUT OF THE XFEL

R. Brinkmann, Deutsches Elektronen-Synchrotron, Hamburg, Germany
for the XFEL Group

Abstract

The X-ray Free Electron Laser XFEL is a 4th generation synchrotron radiation facility based on the SASE FEL concept and the superconducting TESLA technology for the linear accelerator. In February 2003 the German government decided that the XFEL should be realised as a European project and located at DESY/Hamburg. The Ministry for Education and Research also announced that Germany is prepared to cover half of the investment and personnel costs of the project. This paper gives an overview of the overall layout and parameters of the facility, with emphasis on the accelerator design, technology and physics.

INTRODUCTION

X-rays have played for many decades a crucial role in the study of structural and electronic properties of matter on an atomic scale. With the ultra-high brilliant and sub-100 fs pulse length coherent radiation achievable with free electron laser X-ray sources the research in this field will enter a new era [1]. It will become possible to take holographic snapshots with atomic resolution in space and time resolution on the scale of chemical bond formation and breaking. Linear accelerator driven FELs using the principle of self-amplified spontaneous emission (SASE) [2] appear to be the most promising approach to produce this radiation with unprecedented quality in the Å-wavelength regime. The first facility of this type, using part of the existing SLAC linac, was proposed at Stanford and is now under construction [3,4]. The XFEL was originally proposed as integral part of the TESLA project together with a 500 – 800 GeV e+e- Linear Collider based on superconducting RF (SRF) technology [5]. In a later update [6], the proposal was modified such as to build the XFEL with its own, separate linac for the benefit of flexibility regarding construction, commissioning and operation of the facility, maintaining the SRF technology identical to the collider linac and a common experimental site 16km northwest from the DESY site in Hamburg. The German government decision in 2003 to go ahead with the XFEL as a European project and to postpone the decision on the collider led to a revision of the site, with synergy arguments for a common site no longer in effect. The new site layout, sketched in Fig. 1, has the XFEL linac starting on the DESY site, permitting to make optimum use of existing infrastructure, and the user facility in a rural area about 3km west-northwest from DESY. The legal procedure to obtain permission for construction is in preparation and expected to be completed by end of 2005.

The project organisation at the European level is ongoing. A steering committee and two working groups, on scientific-technical and administrative-financial issues,

Figure 1: Sketch of the XFEL site near DESY.

have been established early in 2004, with members from all European countries which are interested in participating in the project. The main task of these groups is to prepare the documents required for the technical definition and organisational structure of the project by 2005. The final decision to move into the construction phase is expected for 2006. The construction time until beam operation will be 6 years. The total project cost is estimated at 684 M€ (year 2000 price level), of which Germany will cover 50%.

The electron beam quality and stability required by the SASE process presents considerable challenges to the linear accelerator community. SASE test facilities in the visible and ultra-violet wavelength range were built and operated during the last years [7]. The results have demonstrated the viability of the challenging accelerator subsystems and the good understanding of the SASE process. In particular the successful operation of the TESLA Test Facility (TTF) linac and FEL at DESY provides a firm basis for the XFEL, regarding the SRF technology, beam dynamics and the FEL process [8] and the conduction of user experiments [9]. In its 2nd phase, just about to start, operation of the VUVFEL, designed for FEL radiation down to 6nm wavelength, will continue to deliver a vast amount of experience as a pilot facility for the future project [10].

OVERALL LAYOUT AND PARAMETERS

The XFEL is laid out as a multi-user facility. In its 1st stage, it will have 5 undulator beamlines, 3 of which are SASE-FELs (two for the Å wavelength regime, one for softer X-rays), the other two for hard X-ray spontaneous radiation. Initially, 10 experimental stations are foreseen. The underground experimental hall has a floor space of $50\times90m^2$ and more stations can be added later. The site allows to extend the user facility for more beam lines in a later stage (see Figure 2).

The undulator sections have a maximum total length of 250m. Variable gap (min. 10mm) type 5m long undulator segments are foreseen, which not only permits to independently adjust the photon energy within certain limits, but also facilitates the precise steering of the electron beam for optimum overlap with the photon beam [11].

Table 1: XFEL Design Parameters

Performance Goals for the Electron Beam	
Beam Energy	10 - 20 GeV
Emittance (norm.)	1.4 mrad × mm
Bunch Charge	1 nC
Bunch Length	80 fs
Energy spread (uncorrel.)	<2.5 MeV rms
Main Linac	
Acc. Gradient @ 20 GeV	23 MV/m
Linac Length	approx. 1.5 km
Inst. Accelerator Modules	116
Installed Klystrons	29
Beam Current (max)	5 mA
Beam Pulse Length	0.65 ms
# Bunches p. Pulse (max)	3250
Bunch Spacing (min)	200 ns
Repetition Rate	10 Hz
Max. Avg. Beam Power	650 kW
Performance Goals for SASE FEL Radiation	
photon energy	15 – 0.2 keV
wavelength	0.08 – 6.4 nm
peak power	24 – 135 GW
average power	66 – 800 W
number photon per pulse	$1.1 – 430 \times 10^{12}$
peak brillance	$5.4 – 0.06 \times 10^{33}$ *
average brillance	$1.6 – 0.03 \times 10^{25}$ *
* in units of photons / (s $mrad^2$ mm^2 0.1% b.w.)	

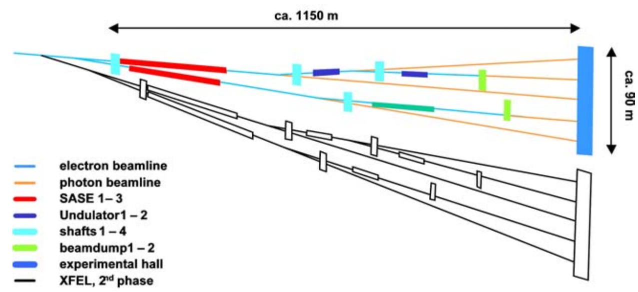

Figure 2: The 1st stage user beamline layout (coloured) and the possible extension.

An overview of the main XFEL parameters is given in Table 1. The undulator parameters have been optimised for one Å wavelength at a beam energy of 17.5 GeV. This implies that at the nominal maximum beam energy from the linac of 20GeV at 23MV/m accelerating gradient, the ^{57}Fe line at 0.08nm, of interest for certain experiments, will be accessible. Furthermore, the expected higher performance of the superconducting cavities (see below) will permit to operate at even shorter wavelength, provided that the electron beam quality can also be further improved to guarantee saturation in the SASE FEL process.

The basic accelerator layout is sketched in Figure 3. The main linac uses 116 12m long accelerator modules with 8 superconducting cavities each, grouped in 29 RF stations. Twelve spare modules, i.e. three RF stations, are included in the design in order to guarantee the overall availability of the accelerator in case of failures. The linac is housed in a tunnel (Figure 4) 15 – 30m underground. The klystrons are in the tunnel and connected to the modulators in an easily accessible surface building on the DESY site by 10kV pulse cables.

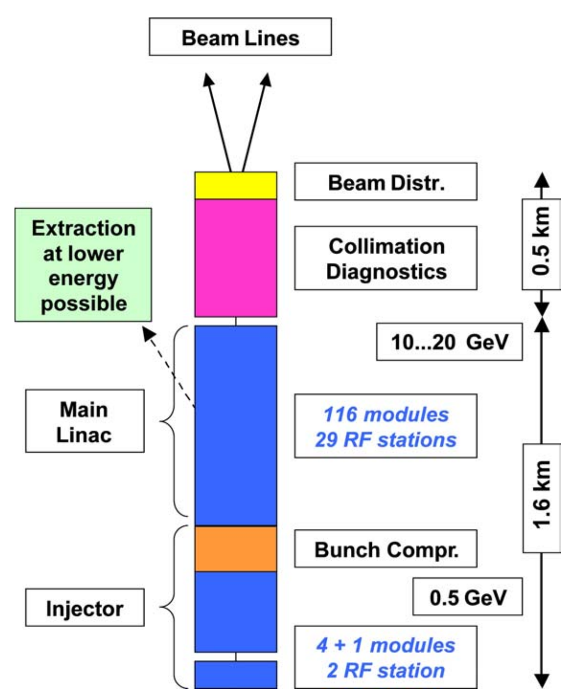

Figure 3: Basic Layout of the XFEL Accelerator.

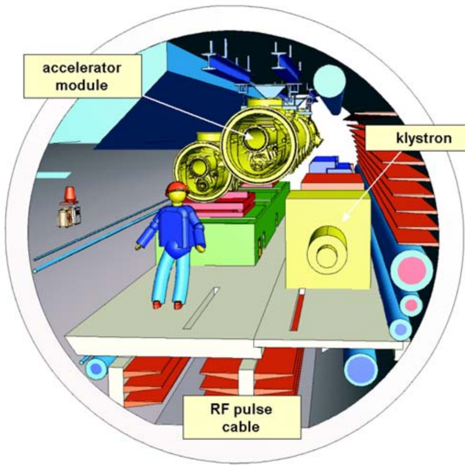

Figure 4: 3-d drawing of the 5.2m diameter main linac tunnel. The accelerator modules will be suspended from the ceiling.

The required klystron power per station is 4.8MW, well below the maximum power of 10MW of the multi-beam klystrons developed in industry for the TESLA project. This will not only cover the power needs for the above mentioned operation at higher energies, but also allow to operate the linac at higher repetition rates (and duty cycles) at lower energy (the main limitation then being the *average* power of the RF system).

In contrast to conventional linacs, with the superconducting accelerator technology even a continuous wave (CW, 100% duty cycle) operation of the linac is conceivable, although only at reduced energy/accelerating gradient in order to avoid excessive cryogenic load into the Helium at 2K. Such an option is not viewed as being part of the initial stage of the facility, but could become attractive if lower-emittance, high duty cycle beam sources become available [12], possibly in combination with advanced FEL concepts. We estimate that with a gradient of 7 – 8 MV/m (~7 GeV beam energy) this mode of operation would be compatible with the foreseen cryogenic plant [13]. A list of preliminary CW-parameters is shown in Table 2. A 2nd , low-power-CW RF system would have to be added, with IOT devices [14] being possible candidates as power source.

Table 2: Preliminary parameters for a possible future CW operation mode of the linac

Beam energy [GeV]	6.5 – 7.5
Acc gradient [MV/m]	7 – 8
Beam current [mA]	0.18
Bunch spacing [µs]	5.5
RF power / module [kW] (incl. regulation overhead)	~20 – 30
Dynamic cryo load 2K [kW]	~2.4 – 3.2

SRF LINAC TECHNOLOGY

The XFEL linac is based entirely on the technology which was over the past years developed by the TESLA collaboration as the most essential part of the R&D programme towards a superconducting linear collider. The successful completion of the 1st phase of the TESLA Test Facility (TTF) has demonstrated that superconducting 9-cell Nb cavities can be reliably produced with the XFEL design performance of 23MV/m. Stable beam acceleration at (or near) this gradient was also demonstrated with complete 12m long accelerator modules, containing 8 cavities each, in the TTF linac [15]. The latest generation accelerator module #5, now installed in the upgraded phase-2 TTF/VUV-FEL (Figure 5), performed in RF tests at a gradient of 25MV/m for all cavities simultaneously (higher for 6 out of 8 in single cavity RF tests) [16]. Several 10MW multi-beam klystrons have been built by industry in France and operated at TTF at design specs. Prototypes from additional vendors are under development [17,18]. Industrialisation of all linac components is one of the crucial tasks on the way towards construction of the machine.

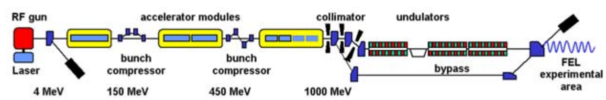

Figure 5: TTF-II and VUV-FEL layout.

The continuing TESLA SRF R&D programme has by now delivered state-of-the-art cavities with a performance well exceeding the XFEL baseline requirements. With the electropolishing (EP) method to improve the Nb surface quality, pioneered at KEK, five 9-cell cavities were tested at gradients of 35 – 40MV/m [19], see Figure 6. One cavity was installed in the first module of the TTF linac and the gradient of 35MV/m previously obtained on the test stand was reproduced in a measurement with beam. The SRF linac for the XFEL will be built with the EP technique and these recent results clearly justify the expectation that the machine will be able to provide the above mentioned flexibility to operate at higher energies without the need to extend the linac length.

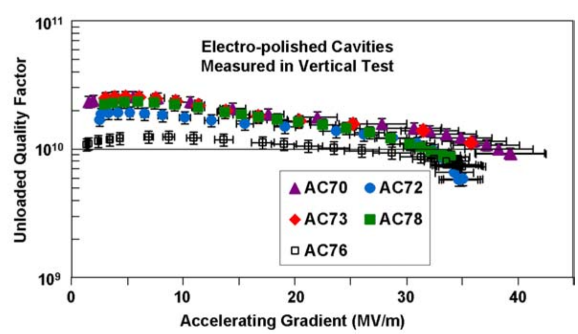

Figure 6: Recent test results for electro-polished TESLA cavities.

INJECTOR AND BUNCH COMPRESSOR

To optimise availability, there are two parallel injectors to produce and accelerate the electron beam before combining the beam lines at roughly 100 MeV. The injector tunnels are shielded from each other, such that maintenance, repair or modifications of one of them is possible while continuing to operate the facility with the other. A short accelerator section at the 3rd harmonic RF frequency is then used for the linearisation of longitudinal phase space. This section is followed by a booster linac increasing the energy to 500 MeV. At this energy the electron bunches are compressed by about a factor of 100 down to $\sigma_z \cong 22\mu m$, corresponding to approx. 5 kA peak current for 1nC charge. A detailed description of this process is given in Ref. [20]. Operation in this extremely short bunch length regime presents considerable technical and beam dynamics challenges, for a recent overview of this subject, see ref. [21].

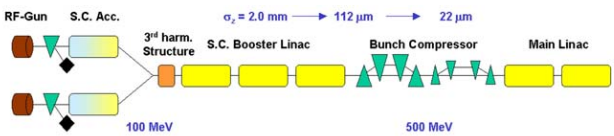

Figure 7: XFEL Injector Layout.

Simulation results for the photocathode RF gun indicate that an rms normalised emittance of 0.9mm×mrad is achievable (see ref. [22] for a recent update). The R&D for low-emittance electron beam sources has been performed within the TESLA collaboration and is supported by the EU Framework Programme 6. Beam tests of the latest version of the RF gun have been done at the PITZ test stand at DESY-Zeuthen [23], yielding a normalised emittance of 1.7mm×mrad. Further improvements are expected by increasing the accelerating field on the cathode from 40 to 60MV/m and optimising the homogeneity of the laser beam profile. The gun previously tested at PITZ is now installed at the VUV-FEL and commissioning with beam has started [24].

The bunch compressor has in comparison to the earlier version [6] been simplified by going from a 3-stage to a single stage layout. This approach turned out to be more robust against the potential problem of the micro-bunching instability. The latter can lead to a strong amplification of initially small modulations in the longitudinal bunch charge distribution by coherent synchrotron radiation (CSR) and space charge effects, unless the uncorrelated energy spread is intentionally increased by 'heating' with a laser [25,26]. The effect of CSR on the beam emittance is in the present layout strongly reduced by splitting up the magnetic chicane of the compressor into a first section with large momentum compaction (transfer matrix element R_{56}) and a second one with small R_{56}. The weak bends in the second section avoid excessive CSR at a position where the bunch becomes shortest. The residual emittance growth obtained from extensive beam dynamics simulations is of the order of 10%, well within the 50% total budget for emittance dilution from the source to the undulators. Further dilution in the downstream main linac is small as a result of very weak wakefields in the TESLA accelerating structures, so that the overall design includes a reasonable safety margin regarding the beam emittance requirements.

The large bunch compression ratio is inevitably connected with tight tolerances on timing, RF phases and amplitude of the gun and the booster section. The effects of jitter in these and other parameters on the FEL photon beam properties have been studied in a model calculations [27]. Even with tight assumptions of 0.05°, 0.02% and 0.1ps in RF phase, amplitude and gun timing jitter (rms) respectively, the fluctuations of photon pulse length and saturation power are not negligible and efficient photon diagnostics are likely required to monitor the beam and correlate variations with experimental data. An advantage of the SRF concept is the possibility to stabilise the RF parameters within a pulse by feedback. An alternative layout with 2 compressor stages is being investigated [28] to asses whether potential advantages regarding jitter tolerances would justify such a 2nd stage.

BEAM DISTRIBUTION

The XFEL linac can accelerate more than 3,000 bunches per RF pulse, serious beam dynamics problems related to higher order modes in the cavities are not expected [29]. User requirements regarding beam time structure will vary over a large range, from single or few bunches to partial or full trains per RF pulse. Generation of such patterns is possible at the source, at the end of the linac or by a combination of both. From the point of view of maximum flexibility a system using programmable fast kickers appears to be the optimum solution. Beam loading conditions in the linac could be quasi static, i.e. the same from pulse to pulse, and bunches could be distributed to different beam lines according to the needs of the respective experiments. The required switching devices are demanding, though, regarding jitter tolerances and reliability. The developments in this direction profit from the R&D work for the linear collider damping ring kickers which have more or less similar requirements. Recently, a very stable kicker pulser was developed at BESSY [30], which appears promising and will be further investigated in the future. In addition to switching the electron beam, it is also possible to switch the FEL process on and off by phase shifters, such that different photon pulse time structures can be generated in a beam line with a sequence of several undulators [31].

The beam transport lattice from the end of the linac to the undulators includes sections for diagnostics and collimation to protect the undulators from potentially large amplitude halo or mis-steered beam. A large momentum acceptance is foreseen so that energy modulation with a bunch train by up to 3% is possible. The lattice layout and the civil construction in the beam distribution region for the 1st phase of the user facility will also already take into account the possibility of later adding more beamlines.

Among the options to add features to the range of possible photon beam properties, very short pulses in the sub-fs regime appear very attractive for certain classes of experiments and could be generated by modulating the energy distribution in the bunch with a very fast laser just upstream from the SASE undulators [32,33].

CONCLUSION

The 20 GeV s.c. linac based on the technology developed by the TESLA collaboration and successfully demonstrated at TTF / VUV-FEL is an ideal driver for the X-ray Free Electron Laser facility, offering a broad range of operating parameters in its baseline design and a considerable potential for future upgrades and options.

With the R&D work progressing towards industrial production of major components and the preparations for the site and the legal procedure (plan approval procedure) well under way, we should be ready to go into the construction phase in ~2 years from now.

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